NOTCH EFFECT TO THE FATIGUE LIFE

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ABSTRACT

This thesis is about the study on the notch effect to the fatigue life on the ASTM 1018 mild steel by using theoretical approach and experiment. The objective of this thesis is to study notch effect to the fatigue life. The thesis describes the stress concentration present on the notched specimen and its effect to the fatigue life on the specimen. The structural three-dimensional solid modeling of both smooth and notched specimen was developed by using the computer aided drawing software, SOLIDWORK 2012. The finite element analysis on the stress distribution was then performed by utilizing MSC NASTRAN. The maximum stress for specimens also was found by calculation using formula. The fatigue lives of both smooth and notched specimens were predicted by calculation using stress-life approach. Manson's approach on notched specimen also used to predict the fatigue for notched specimens. The fabrication for both smooth and notched specimen is conducted by utilizing the computer numerical control lathe machine. Then, the fabricated specimens are tested in rotating bending fatigue by using fatigue test machine. The results were analysis by comparing to theoretical results and found that Manson's approach is the more accurate way to predict the fatigue life for notched specimens. From the results, it found that the notched specimen will have a lot shorter fatigue life compared to the smooth specimen also the fatigue characteristic for both smooth and notch specimen is proven to be different from the observation of distinct fatigue behavior of them.

ABSTRAK

Tesis ini adalah mengenai kajian ke atas kesan takuk kepada hayat lesu pada ASTM 1018 keluli lembut dengan menggunakan pendekatan teori dan eksperimen. Objektif projek ini adalah untuk mengkaji kedudukan kesan kepada hayat lesu. Tesis ini menggambarkan tekanan penumpuan hadir pada spesimen bertakuk dan kesan kepada hayat lesu pada spesimen itu. Pemodelan tiga dimensi struktur kedua-dua spesimen lancar dan bertakuk dibangunkan dengan menggunakan komputer dibantu perisian lukisan, SOLIDWORK 2012. Analisis unsur terhingga terhadap agihan tekanan kemudiannya dilakukan dengan menggunakan MSC NASTRAN. Tekanan maksimum bagi spesimen juga didapati melalui pengiraan menggunakan formula. Hayat lesu spesimen kedua-dua lancar dan bertakuk telah diramalkan oleh pengiraan menggunakan pendekatan tekanan hidup. Pendekatan Manson pada spesimen bertakuk juga digunakan untuk meramalkan fatigue bagi spesimen bertakuk. Fabrikasi untuk kedua-dua spesimen lancar dan bertakuk dijalankan dengan menggunakan komputer kawalan numerikal Lathe mesin. Kemudian, spesimen fabrikasi diuji dalam berputar lesu lenturan dengan menggunakan mesin ujian fatigue. Keputusan itu analisis dengan membandingkan keputusan teori dan mendapati bahawa pendekatan Manson adalah cara yang lebih tepat untuk meramal hayat lesu bagi spesimen bertakuk. Daripada keputusan, ia mendapati bahawa spesimen yang bertakuk akan mempunyai banyak lebih pendek hayat lesu berbanding spesimen yang lancar juga ciri-ciri fatigue untuk kedua-dua spesimen lancar dan kedudukan terbukti menjadi berbeza daripada pemerhatian perlakuan fatigue yang berbeza daripada mereka.

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LIST OF SYMBOLS

ε_s	Surface strain
ϕ	hysteresis angle
N	Fatigue life/ cycle
S_f	Fatigue strength
S_{ut}	Ultimate tensile stress
σ_{max}	Maximum stress
K_f	Fatigue stress concentration factor (Neuber constant)
K_t	Stress concentration factor
S_y	Yield strength
M	Bending moment
I	Moment of inertia
σ_0	Nominal Stress
S_e	Endurance limit
${N_f}^{(n)}$	Fatigue life for notched specimen

LIST OF ABBREVIATION

ASTM	American Society for Testing and Materials
AISI	American Iron and Steel Institute
Fe	Iron
C	Carbon
Mn	Manganese
P	Phosphorus
S	Sulphur
Cr	Chromium
Si	Silica
Ni	Nikel

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In materials science, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material but higher than the endurance limit of the material.

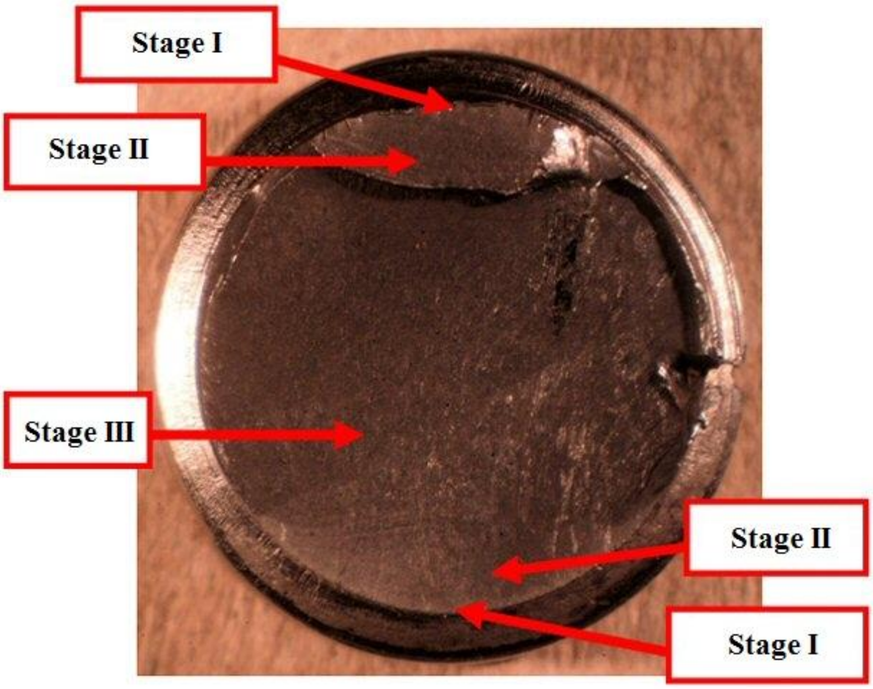

Figure 1.1: Fatigue failure due to reverse bending

Source: http: www.rsime.com

Fatigue occurs when a material is subjected to a continuously of repeated loading and unloading. As shown in Figure 1.1, if the loads are above a certain threshold known as the endurance limit, microscopic cracks or stage I crack will begin to form at the surface. Then the crack will continue to propagate, stage II. Eventually a crack will reach a critical size, and the structure will suddenly fracture, stage III. The shape of the structure will significantly affect the fatigue life; square holes or sharp corners will lead to elevated local stresses where fatigue cracks can initiate. Hence, round holes and smooth transitions or fillets are therefore important to use in designing a structure in order to increase the fatigue strength of the structure.

In many engineering components in service are subjected to various combinations of cyclic and static loadings. Besides, they often contain variety of stress concentrations such as grooves, fillets and holes. Therefore, the local elastic–plastic stresses and strains around the stress riser are frequently in multi-axial situations due to their complex geometrical shape, even under uniaxial loading. It has been observed that fatigue failure of the components usually occur as a result of crack initiation and growth from these stress risers. Thus, correct estimations of stress/strain concentration and crack development especially in the critical region for practical machine design in service loading.

Structure exhibition inevitable geometric discontinuous which are called notches. Such notches can be described by several geometric parameters; the notch length, the notch angle and the notch radius. The present of a notch in a structure is more dangerous than simple reduction net cross section. This effect is generally called the "notch effect". Normally the notch effect is ordinary notch-weakening effect, namely shorter lifetime of notched specimen compared with smooth specimen.

The notch effect in fracture is characterized by the fact that the critical gross stress of a notched structure is less that the critical net stress which acts on the remaining ligament under notch tip. The notch effect in fracture is sensitive to structure geometry, scale effect and loading mode. For in fatigue, even the critical stress at the notch tip is far lower than the ultimate tensile stress of the components; it will have the possibility to fail as the components reach a particular cycle in the cyclic loading. The present of the notch will worsen the condition of the components by having stress concentration at the notch and exceed the fatigue limit further. As a result, the cycle to failure of a notched component will be lower than smooth component.

1.2 PROBLEM STATEMENT

All the moving components may have the risk to fail as fatigue. Fatigue life for a simple beam or bar are predictable, but if there are any discontinuity, sudden change of coss-section, flaw or crack (notch) present that will be a different story. Since the notch will cause stress concentration on it so it will accelerate the failure of the component due to fatigue.

Most engineering components contain geometrical discontinuities, such as shoulders, keyways, and grooves, generally termed notches. When a notched component is loaded, local stress and strain concentrations are generated in the notch area. The stresses often exceed the yield limit of the material in the small region around the notch root, even at relatively low nominal elastic stresses. When a notched component is subjected to cyclic loading, cyclic inelastic strains in the area of stress and strain concentrations may cause formation of cracks and their subsequent growth could lead to component fracture. For cracks that nucleate from a shallow or blunt notch, the fatigue behavior is often dominated by crack nucleation. Cracks that nucleate from a sharp notch often nucleate rather quickly due to the elevated local stresses, and crack growth often dominates the fatigue behavior in this case. Hence, it is important to identify the notch effect in fatigue compare to smooth specimen.

The type of materials used in the experiment is mild steel. Mild steel is the most common high volume steel in production as its price is relatively low while it provides material properties that are acceptable for many applications. Mild steel contains 0.16–0.29% carbon; therefore it is neither brittle nor ductile. Mild steel has a relatively low tensile strength, but it is cheap and malleable; surface hardness can be increased through carburizing. Mild steel have very wide application region from small parts like bolt and nuts to big structure as structural steel in construction and part in the car manufacturing industry. Besides, mild steel is also used to build railway axles a rotating part in train. Hence, these parts will have the risk to fail as fatigue (Madia, 2008). Investigation on the fatigue behavior on mild steel components is vital to ensure the reliability of the component during service.

1.3 OBJECTIVE

I. To study the notch effect contributes to the fatigue life for mild steel.
II. To study the difference of fatigue characteristic between notched and smooth specimens

1.4 PROJECT SCOPE

I. Design smooth and notched specimens using computer modeling software.
II. Fabricate the smooth and notched specimens.
III. Perform stress and strain analysis using MSC.PATRAN and analyzed utilizing the MSC.NASTRAN software.
IV. Perform fatigue analysis using stress-life approach and Manson's Approach for Notched specimen.
V. Compare the fatigue life between the smooth and notched specimens.

1.5 HYPOTHESIS

Notched specimen will have stress concentration at the notch position as a result it will have lower cycle fatigue life compared to smooth specimen.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION OF FATIGUE

Fatigue is the process responsible for the majority of service failures of engineering components and structures, and consequently its many ramifications have been intensively studied by physicists, metallurgists and engineers (Eeles, 1968). The process consists essentially of three separate stages, which is stage I crack initiation, stage II crack propagation and Stage III sudden fracture, which are affected differently by external variables. The mechanisms responsible for the development of these stages, the parameters which control them and the empirical relationships derived for the use of design engineers are discussed on the basis of the most recent available information. The duration for each stage will be depend on the shape of the component like the present of the notch will have totally different duration for each stage of fatigue. Attention is drawn to those areas where further fundamental or applied research is required, and some of the limitations of existing theories are mentioned.

Fatigue is defined by the ASTM as the process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations (Eeles, 1969).

From the continuing efforts of research scientists and engineers throughout the world, there is now a much better understanding of the nature of the mechanism of the fatigue process and of the effect of the numerous operational factors which influence it, although this knowledge tends to be more qualitative than quantitative. It would be fair, therefore, to say that the state of the art is making reasonable progress, but is still a long way from enabling an accurate prediction of the endurance or life of an engineering structure under given service loading and environmental conditions. Hence, the prediction on the fatigue life of the component is for reference. Especially for notched component, the behaviour of it in fatigue is quite peculiar even the critical stress at the notch tip is far lower than the ultimate tensile stress of the components; it will have the possibility to fail as the components reach a particular cycle in the cyclic loading. In engineering application the safety factor should be set high enough to prevent any accident from happening (Eeles, 1969).

The complexity of the fatigue phenomenon is due in part to the fact that progressive fracture is a sequence of at least two processes which are the crack initiation and crack propagation. There may be controlled by two different sets of criteria.

2.1.1 Difference of Flexural Bending and Rotating Bending (Surface strain amplitude ε_s)

Under Flexural Bending

For a round specimen subjected to flexural bending with surface strain amplitude, ε_s which the point that is same distance from the deflection axis αα (strain axis), such as A and B in Figure below, will have exactly the same strain and stress levels. Consequently, these points have the same hysteresis loop as shown in Figure 2.1c. Note that the loading axis ZZ in this case coincides with the deflection axis αα (Megahed, 1995).

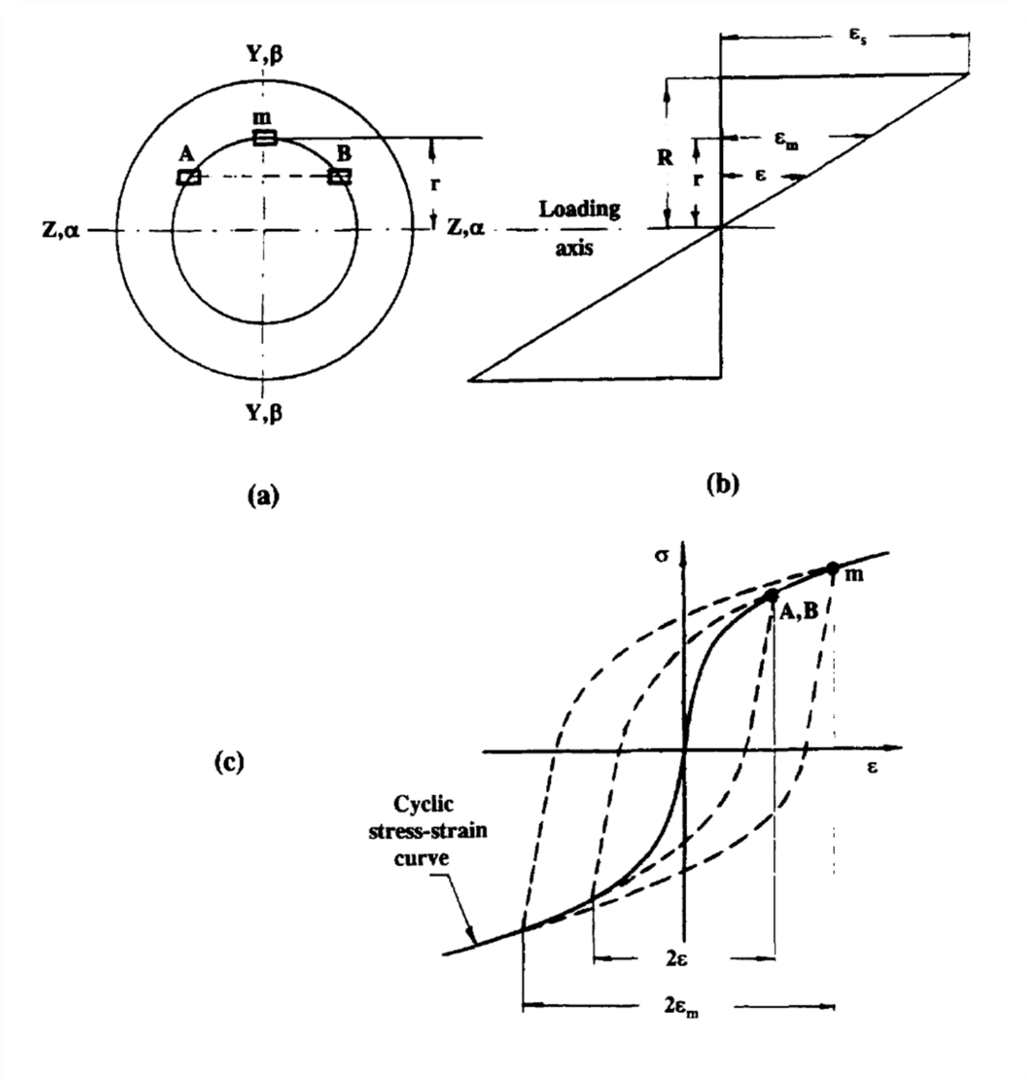

Figure 2.1: Stress distribution in flexural bending from axial strain cyclic properties

Source: Megahed (1995)

Under Rotating Bending

For the same cross-section of the round specimen, now subjected to rotating bending with surface strain amplitude αα. The two elements A and B are at the same distance from the strain axis αα. (deflection axis). Therefore, the two elements are at the same strain level, e, as shown in Figure 2.2b. On the other hand, the two elements now share the same hysteresis loop also, but are not, at any given moment in time, at the same stress level, owing to rotation, as shown in Figure 2.2c. Point A is moving towards a higher stress level, whereas point B is moving towards a lower one. Each point will ultimately reach a maximum strain level era, when they achieve the maximum vertical distance R from the strain axis. Because of rotation, the stress-strain relation for all points along a circle with radius r is represented by one hysteresis loop. Therefore the section will deflect about the axis αα, which makes an angle ϕ with the loading axis ZZ. The angle ϕ is designated the hysteresis angle to indicate the presence of hysteresis loops on the radii of the section.

When the behaviour is elastic, as in high-cycle fatigue, the hysteresis loops degenerate to an elastic line. Therefore the hysteresis angle vanishes. In this case, the rotating bending problem can be treated as a flexural bending problem, wherein the loading and strain axes always coincide.

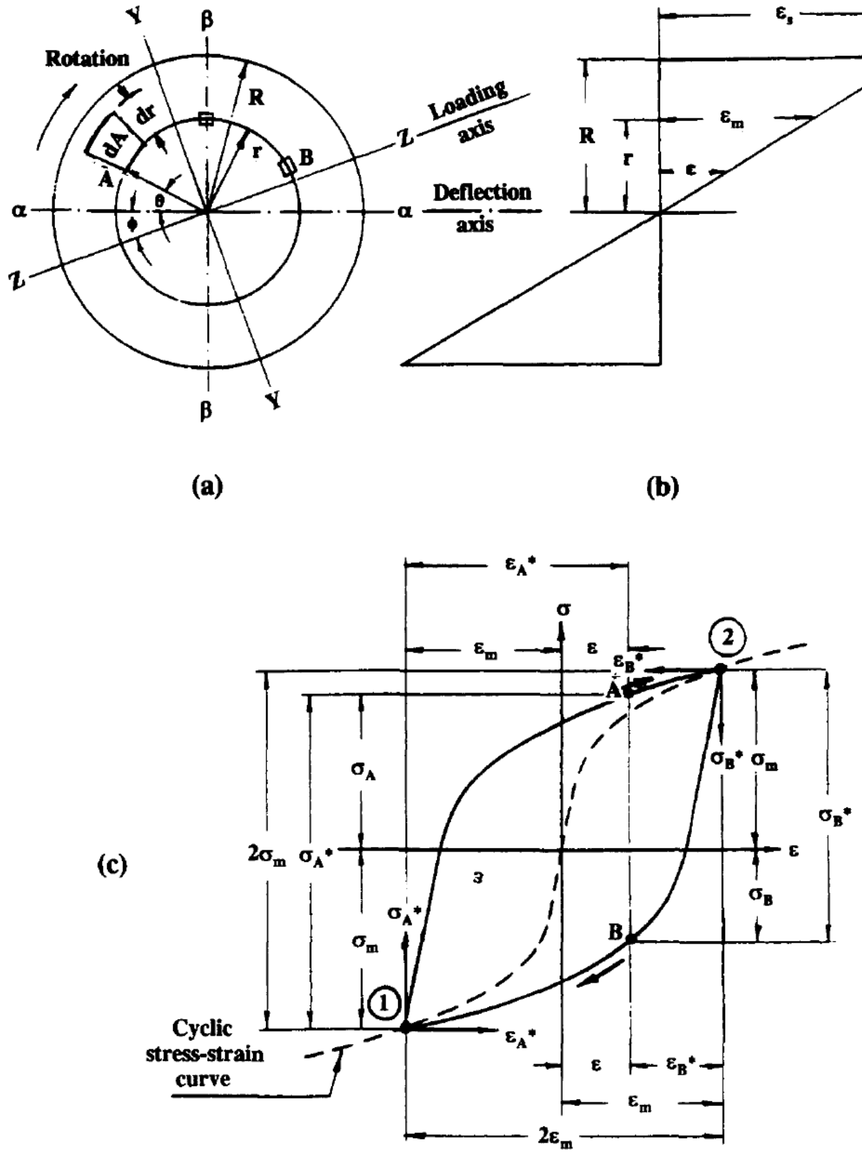

Figure 2.2: Stress distribution in rotating bending from axial strain cyclic properties

Source: Megahed (1995)

2.2 NOTCH

In machines most of its components have notches like shoulder and holes. Most of the time stress concentration will occur at these notches and the maximum stress will also at the same point. So, in order to prevent fatigue failure of the machine's components, it is important to assure the fatigue limit of this kind of components is higher than the maximum stress at the notch root (M. Makkonen, 2001).

2.2.1 Reason of Analyzing the Notch Effect and Behaviour

Most engineering components contain geometrical discontinuities or notches. When a notched component is loaded, local stress and strain concentrations generated at the notch root can exceed the yield limit of the material, even at relatively low nominal elastic stresses. Cyclic inelastic strains may cause nucleation of cracks in the notch region and their subsequent growth could lead to component fracture.

Therefore, accurate evaluation of the deformation and fatigue crack nucleation life of notches are important to reliable performance of notched component behaviour.

2.2.2 Notch Opening Angle Effect

The effect of notch opening angle on the stress concentration factor was considered for the limiting cases. The effect appears to be significant for the shallow notches under torsion, and for the deep notches under bending. It should be noted that for sharp and shallow notches under torsion the stress concentration varies depending on the notch opening angle ω and then the difference between the results of ω=0 and 90° is more than twice (Noda, 2004).

2.2.3 Notch Size Effects

The notch size effect can be explained with two factors which are the statistical size effect and the effect of the stress gradient or called as geometric size effect.

The statistical size effect is when a component is subjected to an alternating load; there will be a number of micro-cracks initiated in its volume. For a larger specimen there will be larger micro-cracks found. Thus, for larger specimen it will have higher probability of large initiated crack and hence lower fatigue limit. According to Makkonen (2001), the size effect in plain specimens is results from the statistical size effect alone. When there is no notch in present, it is clear that the critical crack position wil be at the surface where the maximum stress located.

The geometric size effect comes into picture with notched specimens. The stress distribution in the vicinity of grooves, shoulders and other discontinuities becomes non-linear, and high stress peak will appears. Also, the stress gradient is steeper in small equally shaped specimens. Hence, for a equal-sized crack initiated in two different size specimens the stress intensity factor in crack is higher in a larger specimen.

The size of the specimens is one of the factors that cause variables to the fatigue life. Hence, in the analysis to study the effect of notch to the fatigue life the size of the specimens shall be fixed in order to prevent inaccurate of the result.

2.3 CHARACTERISTIC OF FATIGUE FAILURE IN ROTATING BENDING

The characteristic of fatigue fracture in rotating bending specimen can be separated to three zones (Eleiche, 1995). The first one represents the crack initiation zone. The dark markings running on diagonal directions indicate the presence of various cracks in different planes, which joined up together. This zone has a smooth appearance, owing to the rubbing action as cracks propagate through the tested section. The second zone represents the crack propagation phase with a less smooth appearance, indicating that cracks extended more rapidly. The third zone is the area wherein then final crack occurred, when the net section became too small to support the applied load, and the specimen fractured at this reduced area.

2.3.1 Fatigue Characteristic of Smooth Specimen

For smooth specimen, there seems to be a tendency for the crack to extend preferentially in a direction opposite to that of rotation, in complete matching with the stress distribution over the section under rotating bending, as shown in Megahed, 1995. The more the specimen is restricted within the low cycle fatigue regime, the greater the increase in the hysteresis angle, and consequently the greater the tendency of the crack to propagate in the opposite direction of rotation. Finally, the figure also indicates that most of the file of smooth specimens in rotating bending fatigue tests is attributed to the crack initiation phase. Cracks propagate from one side only while the other side is still within the initiation phase. (Eleiche, 1995; Megahed, 1995).

2.3.2 Fatigue Characteristic of Notched Specimen

For notched specimen, the actual measured lives in virgin notched specimens are greater than the predicted lives based on crack initiation model (Eleiche, 1995). This indicates that notched specimens have extremely longer proportions of lives during the crack propagation phase than those in the initiation phase. These prove the reliability of the investigated materials, wherein the life to propagate a crack from initiation to a critical size is substantial. This provides an additional design margin.

According to Akiniwa (2004), for circumferentially notched specimens, fatigue fracture started from the surface or very near the surface. The slip deformation was responsible for crack initiation in high cycle and very high cycle regimes. The fatigue strength of notched specimens was lower than that of smooth specimens.

2.4 PREDICTION OF FATIGUE LIFE

There are three fatigue life methods used in design and the analyses are the stress-life method, the strain-life method, and linear-elastic fracture mechanic method. These methods attempt to predict the life in number of cycles to failure for specific level of loading. The life of cycle between $1< N< 10^3$ is classified as low cycle fatigue, whereas high-cycle fatigue is considered to be $N > 10^3$ cycles.

2.4.1 The Stress-Life Method

The Stress-Life method (also referred to as the S-N method) was the first approach used in an attempt to understand and quantify metal fatigue. The Stress-Life approach is generally categorized as a high-cycle fatigue methodology, and is still widely used in design applications where the applied stress is primarily within the elastic range of the material and the resulting fatigue lives are long.

The stress-life method is not so suitable in low cycle applications, where the applied strains have a significant plastic component due to the high load level. For these kinds of applications, a Strain-Life Fatigue Analysis is more appropriate.

2.4.2 The Strain-Life Methodology

The strain-life methodology is based on the observation that in many critical locations such as notches the material response to cyclic loading is strain rather than load controlled. This arises from the fact that whilst most components are designed to confine nominal stresses to the elastic region, stress concentrations such as notches often cause plastic deformation to occur locally. The material surrounding the plastically deformed zone remains fully elastic and so the deformation at the notch root is considered to be strain controlled.

The strain-life method assumes similitude between the material in a smooth specimen tested under strain control and the material at the root of a notch. For a given loading sequence, the fatigue damage in the specimen and the notch root are considered to be similar and so their lives will also be similar.

The cyclic stress-strain response of the material at the critical location is determined by characterizing the behavior of smooth specimens subjected to similar loading, the local stress-strain history. The local stress-strain history must be determined, either by analytical or experimental. Stress analysis procedures such as finite element modeling, or experimental strain measurements are usually required.

In performing smooth specimen tests which characterize fatigue performance, it must be recognized that fundamental material properties are being measured which are independent of component geometry. Phenomena such as cyclic hardening or softening, cycle dependent stress relaxation, and loading sequence effects are all taken into consideration.